



Evaluation of global historical land use scenarios based on regional datasets on the Qinghai–Tibet Area

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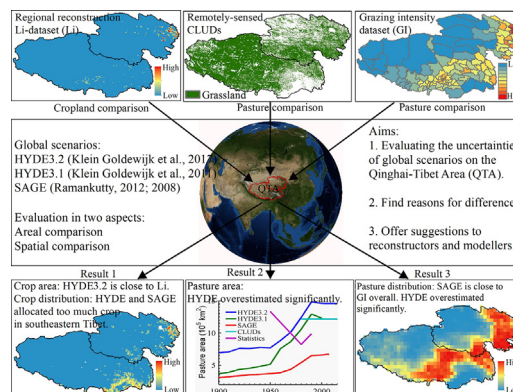
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HIGHLIGHTS

- Grazing intensity was used to assess global historical land use scenarios.
- HYDE substantially overestimated pasture area and distribution on the QTA.
- SAGE pasture distribution matched the spatial pattern of grazing intensity generally.
- FAO pasture definition and reconstruction method are not suitable for the QTA.

GRAPHICAL ABSTRACT



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ABSTRACT

Global historical land use scenarios are widely used to model human-induced climate change from the regional to global scales. It is necessary to conduct regional scale assessments of these global scenarios, identifying their uncertainties and pointing out directions for improvement. Based on the regional reconstruction Li-dataset, remotely sensed dataset, and grazing intensity dataset, the uncertainties of land use area and geographical distribution in HYDE3.1, HYDE3.2, and SAGE (a global land dataset from the Center for Sustainability and the Global Environment) scenarios for the Qinghai–Tibet Area (QTA) are evaluated. The comparisons show that the cropland areas on the QTA in HYDE3.2 for 1900–2000 are close to those of the Li-dataset, whereas HYDE3.1 underestimated and SAGE overestimated the cropland areas significantly. Spatially, HYDE3.1, HYDE3.2, and SAGE have large uncertainties, which cannot reflect the distribution of cropland on the QTA and its changes for 1900–2000 well, and too much cropland is allocated to southeastern Tibet. HYDE3.1 and HYDE3.2 overestimated the pasture area and its distribution on the QTA significantly. The distribution of pasture in SAGE showed overall an agreement with the spatial pattern for grazing intensity, but changes in grazing intensity for 2000–2010 was not reflected in SAGE. The FAO pasture definition and estimates and the method of using population as a proxy for pasture area are not appropriate for the QTA. Methodology which uses the pasture inventory data to calibrate satellite-based grassland maps to obtain the current pasture maps may also not be appropriate because of the lacking differentiation between natural and anthropogenic grasslands in remotely sensed data. More regional

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level land use estimates with concise definitions, define the land use more clearly, and stratification reconstruction based on differences in agro-climatic conditions and resource endowments may be used to improve global maps.

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1. Introduction

Alterations of the planet due to human activity have become substantial and are growing (Venter et al., 2016; Vitousek et al., 1997). For instance, human land use activities have changed the land cover of the earth's surface substantially and played an important role in changing the global carbon cycle, climate, biodiversity, and ecosystem services (Aguilera et al., 2018; de Campos et al., 2005; Ellis et al., 2013; Foley et al., 2005; Vanwallegghem et al., 2017). Due to this, it has been suggested that humans have shifted from living in the Holocene to the Anthropocene which is defined as the geological division arising from humans' impact on the earth (Steffen et al., 2015; Waters et al., 2016). Therefore, many researchers, organizations and academic programs give much attention to land use and land cover change (LUCC) (Lambin et al., 2001; Turner et al., 2007), which is a cause and consequence of global environmental change (Armesto et al., 2010).

As an important part of LUCC and global environmental change, the reconstructions of past land use and related land cover change are necessary to quantify the effects on past climate and environments (Fuchs et al., 2016; Kaplan et al., 2011; Klein Goldewijk et al., 2017; Mallinis et al., 2014). Climate change modelers require spatially and temporally explicit datasets spanning several hundred to thousand years to study the impacts of historical LUCC on the environment. Though remotely sensed datasets provide a globally consistent map of land cover, these data are only available for the past several decades (Houghton et al., 2012; Meiyappan and Jain, 2012). Hence, a number of studies have adopted different approaches to reconstruct historical LUCC in a spatially explicit way.

There are several representative grid-cell based global historical land use scenarios, including anthropogenic land use estimates for the Holocene—HYDE (History Database of the Global Environment) (Klein Goldewijk et al., 2017; Klein Goldewijk et al., 2011); global dataset of croplands and pastures—SAGE (Center for Sustainability and the Global Environment) (Ramankutty, 2012; Ramankutty et al., 2008); anthropogenic land cover change scenario—KK10 (Kaplan et al., 2011; Kaplan et al., 2009); and the Millennium Land Cover Reconstruction—ML08 (Pongratz et al., 2008). In these scenarios, the estimates of historical land use area are based on the human population, the relationship between population and land use, and the UN Food and Agriculture Organization (FAO) land use statistics. These estimates are then allocated into grids employing satellite-based land use maps and land suitability models for cultivation and grazing that consider climate, topography, soil, biome, and distance to rivers. These global historical land use scenarios vary widely, with increasing disagreement for the earlier times (Gaillard et al., 2010; Kaplan et al., 2017; Klein Goldewijk and Ramankutty, 2004; Meiyappan and Jain, 2012), due to the use of different methods and variable definitions of land use for cultivation and animal production (Phelps and Kaplan, 2017). A proper assessment of these global historical land use scenarios is needed together with overall recommendations as to which scenarios appear to be the most realistic.

In addition, such scenarios are widely used to study the impacts of historical LUCC on climate by modelers (Fuchs et al., 2015; Pongratz et al., 2009). Although it has been stated that they only capture the general patterns of land use at the global-continental scale, many studies still rely on them directly to analyze the climate and ecological effects of LUCC at the local-regional scale (Lejeune et al., 2018; Zhao et al., 2018) due to the lack of regional historical LUCC datasets covering a long time period. Also, some studies even use them to analyze the

LUCC spatiotemporal characteristics at the Tibetan Plateau, which obtained anomalous results (Cui and Graf, 2009). So, what is the uncertainty of these global scenarios at the regional scale? To answer this question, it is also necessary to carry out a regional assessment of these global scenarios, identifying uncertainties and pointing out directions for improvement.

Some studies have assessed the uncertainties or accuracy of these representative global scenarios. Kaplan et al. (2017) performed an evaluation of KK10 and HYDE3.1 in Europe using pollen-based reconstruction of the Holocene land cover, suggesting that KK10 shows good agreement with pollen data at country-scale while HYDE3.1 does not. Historical reconstructions over Amazonia (Leite et al., 2012), using census data with high levels of detail, also show considerable differences in spatial patterns and magnitude compared to SAGE scenarios (Meiyappan and Jain, 2012). In China, using global-unique historical-document based reconstructions, researchers evaluated cropland uncertainty in HYDE, SAGE, and ML08 scenarios for traditional agricultural areas of China (He et al., 2013; Zhang et al., 2013) and northeastern China (Li et al., 2010) and concluded that these global historical land use scenarios did not capture the spatial patterns of cropland expansion appropriately for the past 300 years and the mid-eleventh century. It can be concluded that regional comparisons are increasingly being undertaken, but mostly for cropland and not for pasture because of imprecise land use/cover definitions and lacking characterization of animal production systems (Phelps and Kaplan, 2017).

Historical reconstructions in China have focused mainly on cropland for the mid-eastern regions of the country (Miao et al., 2013; Yang et al., 2018). The Qinghai–Tibet Area (QTA) is a traditional pastoral area of China for which historical records concerning land use are rare (Li et al., 2017). The reconstruction of historical land use, especially pasture, however, is valuable for identifying human–environment interactions in alpine regions, and many scholars have paid attention to reconstructing past environments of the QTA (Chen et al., 2015; Dunn et al., 2018). To reconstruct historical land use of the QTA properly, it is necessary to assess global scenarios in this region.

The primary aim of this study is to evaluate the uncertainty and accuracy of global scenarios in estimating land use area and in reproducing the spatial patterns of cropland and pasture for the QTA based on regional reconstructions, remotely sensed land use dataset, and grazing intensity dataset. Considerations are also given concerning the possible reasons for differences between the global scenarios and the regional reconstructions. Recommendations and suggestions are also provided to aid re-constructors and climate change modelers.

2. Brief description of the Qinghai–Tibet Area

The QTA is the largest and highest mountain region on earth (Miehe et al., 2018; Yao et al., 2012). It stretches from the Pamir and Hindu Kush in the west to the Hengduan Mountains in the east, from the Kunlun and Qilian mountains in the north to the Himalayas in the south (Fig. 1). It is known as the Third Pole (besides the North and South Poles) of the world, and the mean elevation of the region is greater than 4000 m (Miehe et al., 2018). It is also referred to as Asia's Water Tower (Immerzeel et al., 2010) with the Yellow River, the Yangtze River, and the Lancang-Mekong River originating from here and providing water resources for nearly 40% of the world's population. It is a hotspot of biodiversity conservation for the world (Myers et al., 2000) and most regions are covered by alpine meadows and alpine grassland

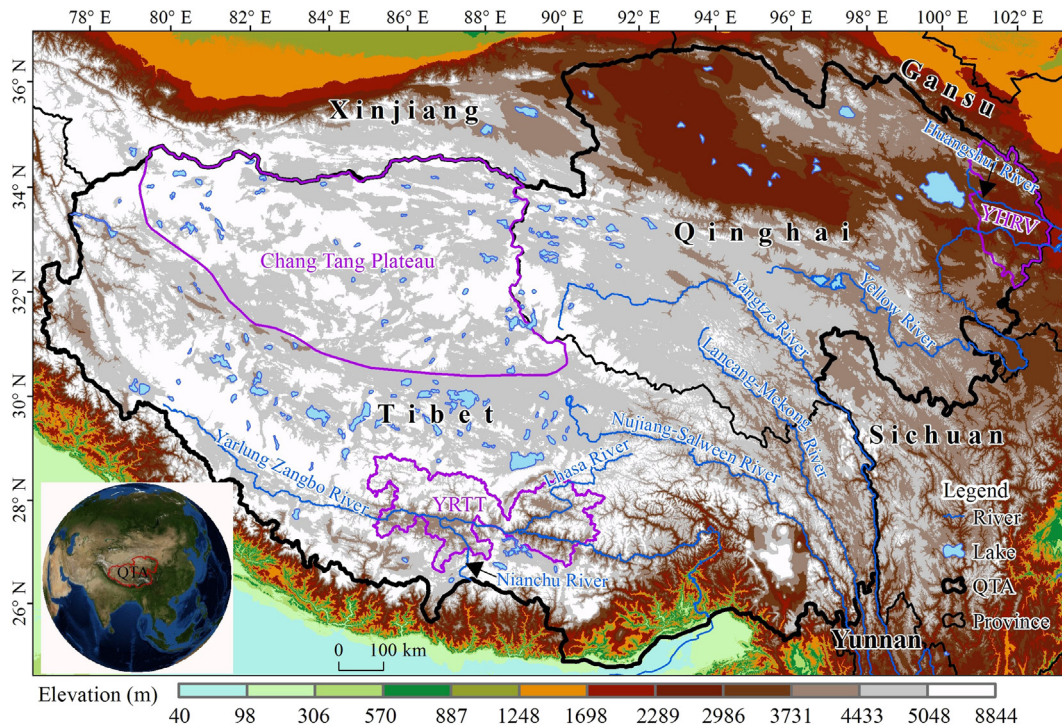


Fig. 1. Location of the Qinghai-Tibet Area (QTA). The top-right purple polygon is the Yellow-Huangshui Rivers Valley (YHRV), the middle-bottom polygon is the Yarlung Zangbo River and its Two Tributaries (YRTT) valley, and the middle-left polygon is the Chang Tang Plateau.

ecosystems (Hou, 2001a) which are very fragile and sensitive to human activities (Fan et al., 2010; Wu et al., 2019).

The intensity of human activity on the QTA is low overall, and the mid-western parts of Tibet (e.g., the Chang Tang Plateau) is referred to one of Earth's remaining wilderness areas in the Anthropocene (Watson et al., 2016), but the intensity of activities has been increasing in recent years (Fan et al., 2015; Li et al., 2018b; Mieke et al., 2014; Venter et al., 2016). People and reclamation activities are mainly distributed in the Yellow-Huangshui Rivers Valley (YHRV) of the northeastern Qinghai Province and the midstream of the Yarlung Zangbo River and its Two Tributaries (the Lhasa and the Nianchu Rivers. Hereafter YRTT for short) region (Li et al., 2017). Because both the regional reconstructions and grazing intensity dataset are political-polygon based data, so the QTA, i.e., Qinghai Province and Tibet with areas of 72.10×10^4 and 122.84×10^4 km² respectively, is set as evaluation region for the global scenarios in this study (Fig. 1).

3. Materials and methods

3.1. Materials

First, the global historical land use scenarios are outlined and then a description is given of the reference datasets, including regional cropland reconstructions, remotely sensed land use/cover dataset, and grazing intensity dataset for the QTA.

3.1.1. Global land use scenarios

As mentioned in the Introduction, there are several representative global land use scenarios, including HYDE, SAGE, KK10, and ML08. In this study, based on the time period covered in the regional reconstructions and the remotely sensed dataset, only the global land use scenarios covering the period 1900–2000 were evaluated. The KK10 scenario covers the period 8 ka–1850 CE, which is outside the evaluation period of this study (Kaplan et al., 2011). The ML08 scenario focuses mainly on the period 800–1700 CE (Pongratz et al., 2008) and its data for the period 1700–1992 were revised from SAGE and HYDE. Thus, we evaluated the HYDE (versions 3.1 and 3.2) and SAGE scenarios and details of them are summarized in Table 1.

3.1.1.1. HYDE scenarios. HYDE (History Database of the Global Environment) is a database compilation of cropland and pasture data which is consistent with the FAO land use statistics definition of “arable lands and permanent crops” and “permanent pastures”, respectively. Historical cropland and pasture inventory data in HYDE for the post-1960 period have been taken directly from the FAO land use statistics and for the pre-1960 period were estimated using the FAO per capita cropland and pasture areas for 1960 and the historical population data assuming that the per capita values were constant, or slightly increased or slightly decreased over time (Klein Goldewijk et al., 2017; Klein Goldewijk et al., 2011). Using current satellite-based spatial patterns for cropland and potential natural vegetation and several other weighting maps,

Table 1

Details of global historical land use scenarios, regional reconstruction for the Qinghai-Tibet Area (Li-dataset), remotely sensed dataset (CLUD), and grazing intensity dataset (GID).

Datasets	Temporal coverage	Thematic coverage	Spatial resolution	Reference
HYDE3.1	10,000 BCE–2000 CE	Cropland, pasture, built-up land	5'	Klein Goldewijk et al. (2011)
HYDE3.2	10,000 BCE–2015 CE	Cropland, pasture, built-up land	5'	Klein Goldewijk et al. (2017)
SAGE	1700–2007 CE	Cropland, pasture	0.5°	(Ramankutty, 2012; Ramankutty et al., 2008)
Li-dataset	1900–2000	Cropland	1 km	Li et al. (2017)
CLUD	1980–2015 CE	Cropland, woodland, grassland, water bodies, built-up land, unused land	1 km	Liu et al. (2014)
GID	2000, 2010	Standardized sheep units per unit grassland area	County level	(Ouyang et al., 2014; Ouyang et al., 2016)

historical cropland and pasture inventory data are allocated into grids with a resolution of 5 min. The initial version of HYDE covered only the last 300 years (Klein Goldewijk, 2001), and HYDE3.1 (Klein Goldewijk et al., 2011) extended the period from 10,000 BCE to 2000 CE. The latest version, HYDE3.2 (Klein Goldewijk et al., 2017), provides new features regarding reconstructed cropland and grazing land.

3.1.1.2. SAGE scenario. The SAGE database also adopted the FAO definition of “arable lands and permanent crops” and “permanent pastures”. The estimates rely more on (sub) national-level census statistics, along with FAO estimates for recent years (Ramankutty et al., 2008; Ramankutty and Foley, 1999). The SAGE cropland dataset for 1700–1992 (Ramankutty and Foley, 1999) and the pasture dataset for 2000 (Ramankutty et al., 2008) are based on two assumptions. First, the satellite-based spatial pattern for 1992 represents the historical spatial patterns within each political unit. Second, the historical inventory data can provide the temporal information needed to describe the differences in cropland and pasture area among the political units. Later, the authors expanded the temporal period for the global cropland and pasture dataset to 1700–2007 using population as a proxy for land use area and satellite-based spatial patterns as a proxy for historical patterns (Ramankutty, 2012).

The land use statistics in HYDE and SAGE show substantial disagreement globally (Klein Goldewijk and Ramankutty, 2004), with even more regional disagreement, particularly for the developed Pacific region and China (He et al., 2013; Meiyappan and Jain, 2012; Zhang et al., 2013).

3.1.2. Reconstructions in the Qinghai–Tibet Area

Historical records on land use for the QTA are rare because of the harsh natural environment, low level of economic activity, and low population density. Thus, it is difficult to reconstruct land use datasets covering a long time period for this remote region. In the study of Li et al. (2017), the provincial cropland area for Qinghai and Tibet over the 20th century was estimated. For 1900, 1930, and 1950, the cropland area was estimated using provincial population data as a proxy on the assumption that the per capita cropland area was constant for the first half of the 20th century given that no significant improvement in agricultural technology and productivity had occurred on the QTA for this period. The per capita cropland area of 1953 was determined from a comprehensive field investigation on cropland area and grain yield (Feng et al., 2005). Compared with the FAO per capita cropland area value for this period for the whole of China in the global scenarios, the per capita cropland area of Li et al. (2017), which was derived from field investigations at the regional scale, is considered more accurate. The provincial population data were obtained from the Chinese Population History (5th and 6th volumes) (Cao, 2001; Hou, 2001b), which is a rigorous estimation based on historical population records by historical geographers. For 1980, the provincial cropland area was estimated using the relationship between cropland area and grain yields given that the statistical data was underestimated (Frolking et al., 2002; Liu et al., 2005). For the year 2000, the statistical data were evaluated and considered to be accurate, and were used. Then, using land suitability for cultivation model and the maximum cropland distribution as determined by China's remotely sensed Land Use/Cover Datasets (CLUDs), the provincial cropland area was allocated into grids with a resolution of 1 km × 1 km. A comparison with previous studies indicated good accuracy for this spatially explicit cropland dataset (Li et al., 2016; Luo et al., 2014). So, the dataset was used as a reference dataset to evaluate cropland in the global scenarios. This dataset is termed the Li-dataset, hereafter.

Historical pasture reconstruction for the QTA is rare and spatially explicit datasets covering a long time period are not available due partly to the fact that it is difficult to distinguish between natural grassland and pasture. The grassland/pasture statistics of Qinghai Province and Tibet for 1950, 1980, and 1990 from the national agricultural statistics (Wu

and Guo, 1994) are available. And for the statistics, grassland/pasture is a general term for herbaceous vegetation and includes both natural and anthropogenic grassland, as well as deserts, shrubs, and sparse forest for grazing purposes (Wu and Guo, 1994). For thousands of years, the land use practices in China have evolved that cropland has been expanding with population growth, which has led to a decline in grassland area and shrinking spatial distribution (He et al., 2018; Ye and Fang, 2011). The grassland area tendency reflected by the statistics shows good agreement with this land use practice and some previous studies for the QTA (Li et al., 2013; Liu et al., 2008; Wu, 2017) and studies for whole China for 1935–1997 (Ge et al., 2008; Ge et al., 2000). Therefore, it is used in this study to compare with the pasture inventory data in the global scenarios. Taking the difference in definition into account, the pasture inventory data in global scenarios may well be less than the statistical grassland/pasture areas.

3.1.3. Remotely sensed land use/cover datasets of China

Spatial patterns of HYDE and SAGE scenarios were reconstructed using remotely sensed maps, so CLUDs is used for evaluating the uncertainties in these global scenarios. Based on Landsat TM/ETM data and using visual interpretation methods, Liu et al. (2014) reconstructed CLUDs at 1 km resolution with six classes of land use/cover types, including cropland, woodland, grassland, water bodies, unused land, and built-up land for 1980, 1990, 1995, 2000, 2005, 2010, and 2015 (<http://www.resdc.cn/>).

Grassland in CLUDs means land covered by herbaceous vegetation with coverage greater than 5%, including shrub rangeland and mixed rangeland with the coverage of the shrub canopy being less than 10%. The grassland was categorized into dense, moderate, and sparse grasslands (Liu et al., 2014; Liu et al., 2005). These categories included grassland for grazing, and grassland not used or not suitable for grazing. It can be seen that the scope for grassland as defined in CLUDs is greater than that for pasture that is used for grazing in HYDE and SAGE scenarios, especially in the QTA which is a traditional pastoral region of China with an established system of grassland-based livestock (Verburg and van Keulen, 1999).

In China, a reliable spatially explicit historical pasture distribution layer is unavailable, even for the present day (Shen et al., 2016). So, a grassland layer with a 1 km resolution (in CLUDs) is used in the present study to assess roughly the uncertainty of pasture as represented in HYDE and SAGE scenarios. The area and spatial scope of pasture in HYDE and SAGE scenarios must be less than the area and spatial scope of grassland in CLUDs since the scope for grassland as defined in CLUDs is greater than that for pasture in HYDE and SAGE scenarios.

3.1.4. Grazing intensity dataset

Comparisons between pasture in HYDE and SAGE scenarios and grassland in CLUDs should only be judged as an initial evaluation given that the terms pasture and grassland are not defined in the same way. A comparison between pasture in HYDE and SAGE scenarios with grazing intensity, which can be denoted by standardized sheep units per unit grassland area, may be attempted. To support the number of livestock in a certain region, there must be a corresponding area of pasture in the region, particularly so for historical periods when human mobility would have been limited and given the difficulties of conducting trade between remote and outside regions. So, the spatial pattern of grazing intensity is highly correlated with pasture distribution (Ramankutty et al., 2008).

The grazing intensity at the county scale for the QTA was cited from China's first national ecosystem investigation and assessment (2000–2010) program, which was launched by the Ministry of Environmental Protection and the Chinese Academy of Sciences. This program aimed to quantify the ecosystem status and trends between 2000 and 2010 (Ouyang et al., 2016; Sugden, 2016). First, the number of livestock surveys for a year is converted into sheep unit (e.g., one sheep/goat is equivalent to one sheep unit, one cow is equivalent to five sheep

units, and one horse is equivalent to six sheep units), and then the sheep unit is divided by the grassland area to obtain the grazing intensity datasets (http://www.ecosystem.csdb.cn/ecogi/tpclasses_detail.jsp?id=EA1304CD2A799690CF51D02F72F7707F). Note that the seasonal changes in livestock distribution are not considered in the datasets. The spatial pattern of this grazing intensity dataset show good agreement with previous studies (Verburg and van Keulen, 1999; Zhao et al., 2015) and has been widely used to assess the human impact on ecosystems (Li et al., 2018b).

3.2. Evaluation methods

For cropland, comparisons between the global scenarios and the Li-dataset were carried out and the comparison time period was set to 1900–2000, taking the temporal coverage for the Li-dataset into account (Fig. 2). For pasture, no spatially explicit historical dataset is available at the regional scale, so the global scenarios were compared with grassland/pasture inventory data for 1950–1990, grassland in CLUDs for 1980–2015, and grazing intensities for 2000 and 2010.

The spatial resolutions of HYDE (versions 3.1 and 3.2) and SAGE are 5 min (~10 km at the Equator) and 0.5° (~60 km at the Equator), respectively. The grid cell sizes of the Li-dataset and CLUDs are 1 km, and the grazing intensity is at the county scale, so the spatial comparison for HYDE3.1 and HYDE3.2 was conducted at the 10 km scale and for SAGE the comparison was performed at the 60 km scale. The Li-dataset and CLUDs were resampled to 10 km and 60 km, respectively, for comparison purposes.

First, areal comparisons for cropland and pasture were carried out. Then spatial comparisons at the grid scale were conducted. Spatial comparison for cropland was carried out between the global scenarios and the Li-dataset for 1900, 1930, 1950, 1980, and 2000. Spatial comparisons for pasture were carried out between the global scenarios and CLUDs and grazing intensity for 2000 and 2010 (Fig. 2).

4. Results

4.1. Differences in estimates of cropland area

The cropland areas of the QTA for 1900–2015 from HYDE3.1, HYDE3.2, SAGE and the Li-dataset are illustrated in Fig. 3. There is a good agreement between HYDE3.2 and the Li-dataset for 1900–2000 because of updating of the regional reconstructions in HYDE3.2 (Klein Goldewijk et al., 2017). SAGE gave an overestimation of the cropland area by more than 50% for the whole period compared with the Li-dataset. As for HYDE3.1, the cropland area was lower than that for the Li-dataset by about 500% before 1990 and significantly greater than the Li-dataset after 1990.

Three stages of change for cropland area over the 1900–2000 period can be detected for the Li-dataset, namely, a stable stage for 1900–1950, a rapid growth stage for 1950–1980, and a stable stage for 1980–2000 (Fig. 3). However, the SAGE and HYDE3.1 scenarios show that the cropland area for 1900–1980 increased linearly; and after 1980 SAGE increased with fluctuations, whereas, HYDE3.1 increased exponentially, which clearly is not reasonable. It can be seen that the cropland area for HYDE3.2 increased linearly for 1900–1960 and then increased with some fluctuations for 1960–2005, and then decreased slightly for 2005–2015, indicating differences from the Li-dataset, especially for the period 1960–1980. The population of Qinghai and Tibet increased from 3.76 million in 1960 to 5.62 million in 1980 based on census data, which implies that more cropland area would have been needed for this period given that the per capita cropland area was nearly constant. The land use estimates for the post-1960 period in HYDE3.2 were taken from the FAO land use statistics and the area for the pre-1960 period was estimated using the population and the per capita cropland area. The connectivity between the two time periods is not smooth, and the uncertainty of cropland area, based on the FAO data for the post-1960 period, may propagate to HYDE3.2.

4.2. Differences in estimates of pasture area

The data for HYDE3.1, HYDE3.2, and SAGE show that the pasture area on the QTA increased slowly for 1900–1950, increased rapidly for 1950–1990, and then remained relatively stable after 1990. These trends differed from the trends in the statistical data and CLUDs. Based on the statistical data, the grassland/pasture area decreased significantly from 1950 to 1980 and then recovered slightly for 1980–1990. CLUDs indicated that the grassland area remained nearly stable for 1980–2015 (Fig. 4).

In terms of magnitude, the pasture areas for the QTA in HYDE3.1 and HYDE3.2 were clearly greater than the statistical grassland/pasture data for 1970–1990, and the values were also greater than the grassland area in CLUDs for 1980–2015 (Fig. 4). As mentioned previously, the definitions of grassland/pasture in the statistical data and grassland in CLUDs are broader than that for pasture in the global scenarios, so HYDE3.1 and HYDE3.2 overestimated significantly the pasture area for 1970–2015. The pasture areas of HYDE3.1 and HYDE3.2 for 1960–2015 were from the FAO, indicating that the FAO pasture inventory data for 1970–2015 were also an overestimate of the pasture area for the QTA.

Besides, we infer that great uncertainty exist in the slow increase trend of pasture area for 1900–1950 and rapid increase trend for 1950–1990 in HYDE3.1 and HYDE3.2 based on previous regional studies which suggested a decrease of grassland/pasture area for the Qinghai Province over the 20th century (Ge et al., 2008; Ge et al., 2000; Wu, 2017). Since the end of the Qing Dynasty (1661–1911 CE), the Qinghai

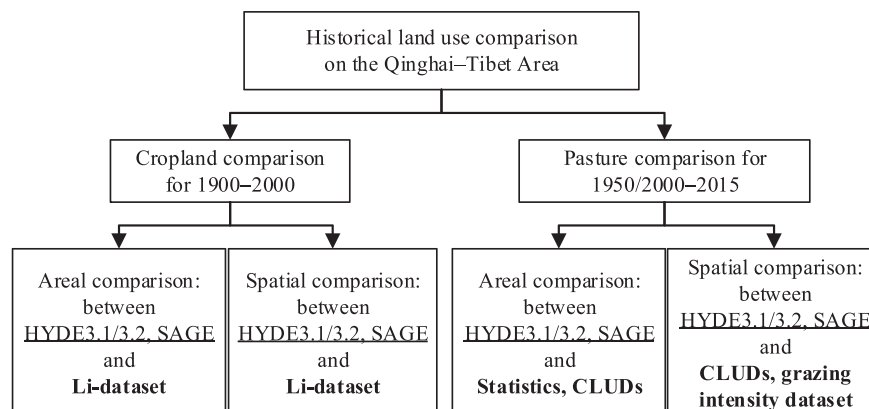


Fig. 2. Overview of the comparisons undertaken between the global scenarios (underlined) and the regional datasets (bold).

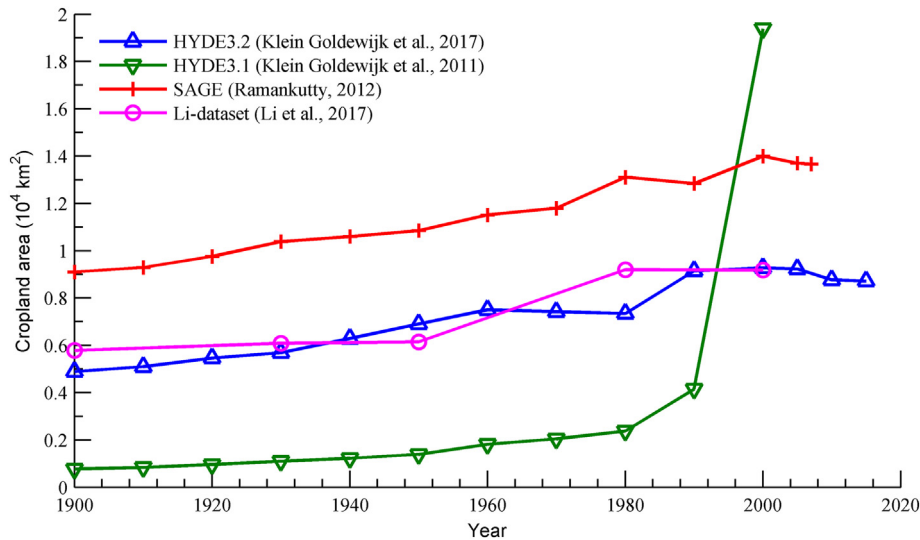


Fig. 3. Cropland areas of the Qinghai-Tibet Area for 1900–2015 from the various datasets.

provincial government has attached great importance to the agricultural economy and they even established the bureau of reclamation and carried out several large-scale grassland/pasture reclamations. As a result, the grasslands in Qinghai Province were constantly being reclaimed as cropland (Ge et al., 2008). A regional study for the YHRV in the northeast QTA for the Qing Dynasty and the Republic of China (1912–1949 CE) also indicated that the grassland/pasture area decreased significantly for this period (Wu, 2017). Continuous grassland/pasture degradation and the extension of desertification and salinization in the “Three-River Headwaters (the Yellow River, the Yangtze River, and the Lancang-Mekong River)” region of the Qinghai Province over the period 1960s–2000s were also detected (Li et al., 2013; Liu et al., 2008). The national scale data also suggested that the grassland/pasture area (the definition is same as Wu and Guo (1994)) of China decreased significantly for 1935–1997 (Ge et al., 2000). The difference in pasture area between HYDE3.1 and HYDE3.2 after 1960 was due mainly to the improvement of the allocation algorithm.

In SAGE, the pasture area was calibrated and grazed forestland and semiarid land were excluded from the FAO estimation (Ramankutty et al., 2008). The FAO pasture inventory value was 4 million km² for China, whereas the estimated area for SAGE was 2.9 million km²

which is similar to the results of Verburg et al. (2000). Fig. 4 shows that the pasture area of the QTA in SAGE for 1950–2007 was less than the grassland area from CLUDs and statistics, which is reasonable, considering the differences in definition between grassland and pasture. But more comparison is needed for a comprehensive evaluation on the uncertainty of pasture area in SAGE on the QTA.

4.3. Differences in spatial patterns of cropland

4.3.1. Comparison between HYDE3.1 and the Li-dataset

Large differences exist between HYDE3.1 and the Li-dataset for the spatial patterns of cropland on the QTA (Fig. 5). HYDE3.1 shows that the cropland on the QTA was little for 1900, 1930, and 1950, which was mainly distributed in the YHRV regions. But more cropland can be detected in the Li-dataset, not only in the YHRV regions but also in the YRTT regions and eastern Tibet. And the cultivation intensity for the YHRV regions shown in the Li-dataset was also greater significantly than that in HYDE3.1. The extensive negative differences which are greater than 40% for most grids in the YHRV regions between HYDE3.1 and the Li-dataset for 1900–1950 also indicated the underestimation of cropland area in HYDE3.1.

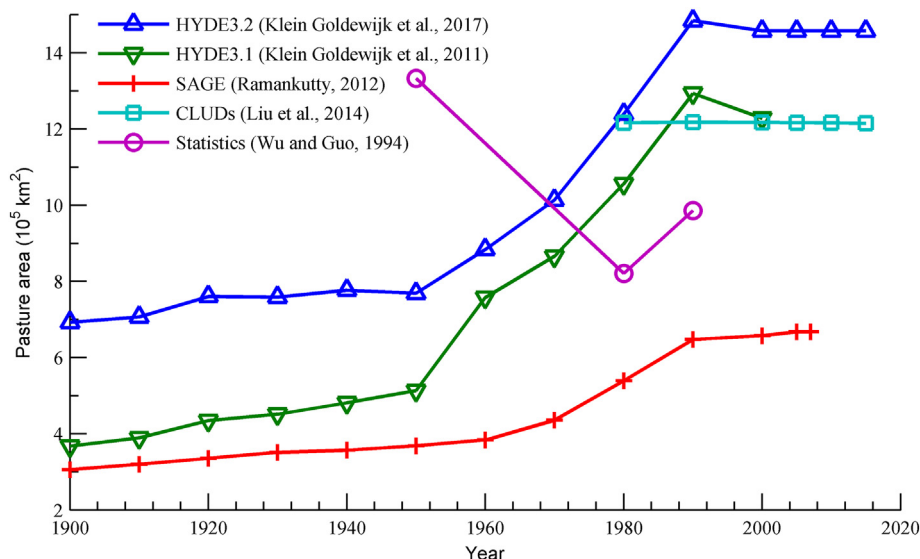


Fig. 4. Pasture areas of the Qinghai-Tibet Area for 1900–2015 from the various datasets.

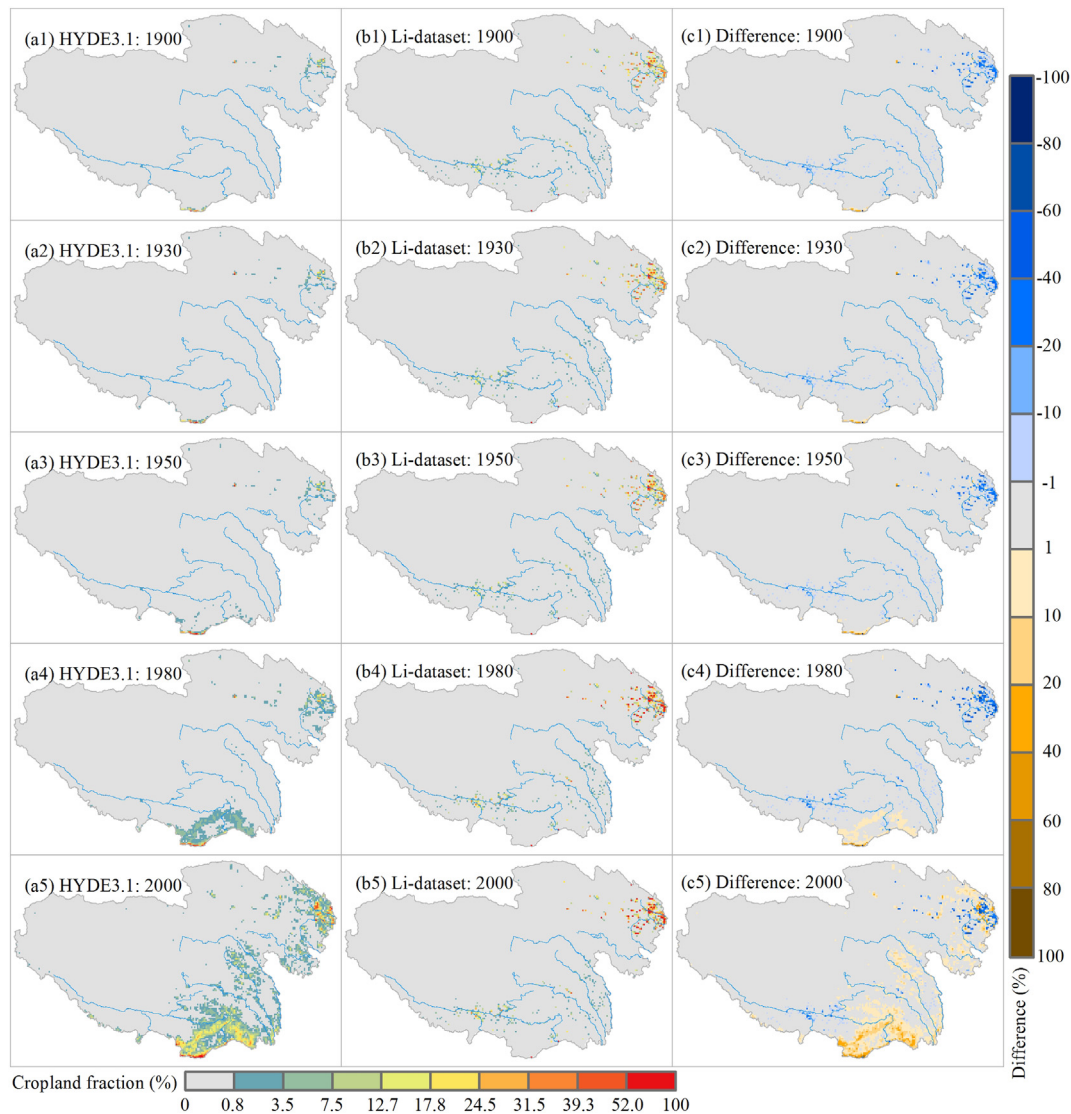


Fig. 5. Comparison of spatial patterns of cropland between HYDE3.1 and the Li-dataset for 1900–2000 on the Qinghai–Tibet Area.

HYDE3.1 suggests that the cropland on the QTA expanded significantly for 1950–2000 in the YHRV and southeastern Tibet regions, especially for 1980–2000 in eastern Plateau, which is different from the spatial patterns of cropland and its change tendency reflected in the Li-dataset substantially. It is highly unreasonable that so much cropland distribution and expansion occurred for 1980–2000 in southeastern Tibet and eastern Plateau regions where woodland is dominated land cover type based on satellite images (Fig. S1 in Supplementary material) and vegetation atlas of China (Hou, 2001a). And extensive positive differences detected in these regions (Fig. 5(c5)), which is even greater than 40% for some grids in southeastern Tibet. Additionally, the extensive negative differences in the YHRV and YRTT regions indicated the underestimation of cropland area in HYDE3.1 for these places. Finally, it can be concluded that great uncertainties exist in HYDE3.1 not only in terms of the absolute cropland area and its increasing tendency (Fig. 3), but also in terms of the spatial distribution of cropland and its expansion for 1900–2000 (Fig. 5).

4.3.2. Comparison between HYDE3.2 and the Li-dataset

Generally speaking, HYDE3.2 and the Li-dataset both show that cropland of the QTA is distributed mainly in the YHRV of northeastern Qinghai Province, and in the YRTT of Tibet (Fig. 6). However, the extent

of cropland distribution in HYDE3.2 is greater than that in the Li-dataset not only in the regions mentioned above, but also in southeastern Tibet, where there is no large amount of reclamation activities because of complex terrain, which clearly is unreasonable.

For the 1900–1950 period, the spatial patterns of cropland and cultivation intensity on the QTA were stable as shown in the Li-dataset (Fig. 6). However, HYDE3.2 showed that the spatial extent of cropland shrank in western Qinghai, but expanded in eastern and southeastern Tibet, and intensified slowly in YHRV. It can also be seen that the number of grids with a minus difference decreased in YHRV for this period. For 1950–1980, the Li-dataset showed that the cultivation activities intensified in YHRV and YRTT while this trend was not reflected in HYDE3.2, and the number of grids with a minus difference increased in YHRV and YRTT. Over the last 20 years of the 20th century, the Li-dataset showed that the spatial pattern for cropland on the QTA was relatively stable, but in HYDE3.2, the cropland expanded significantly on the QTA and intensified in YHRV; and the number of grids with a minus difference decreased.

In addition, the difference maps for the five periods show that the differences between HYDE3.2 and the Li-dataset in southeastern and eastern Tibet were positive, indicating too much cropland was allocated to these areas by HYDE3.2. It can also be seen that the distribution of the

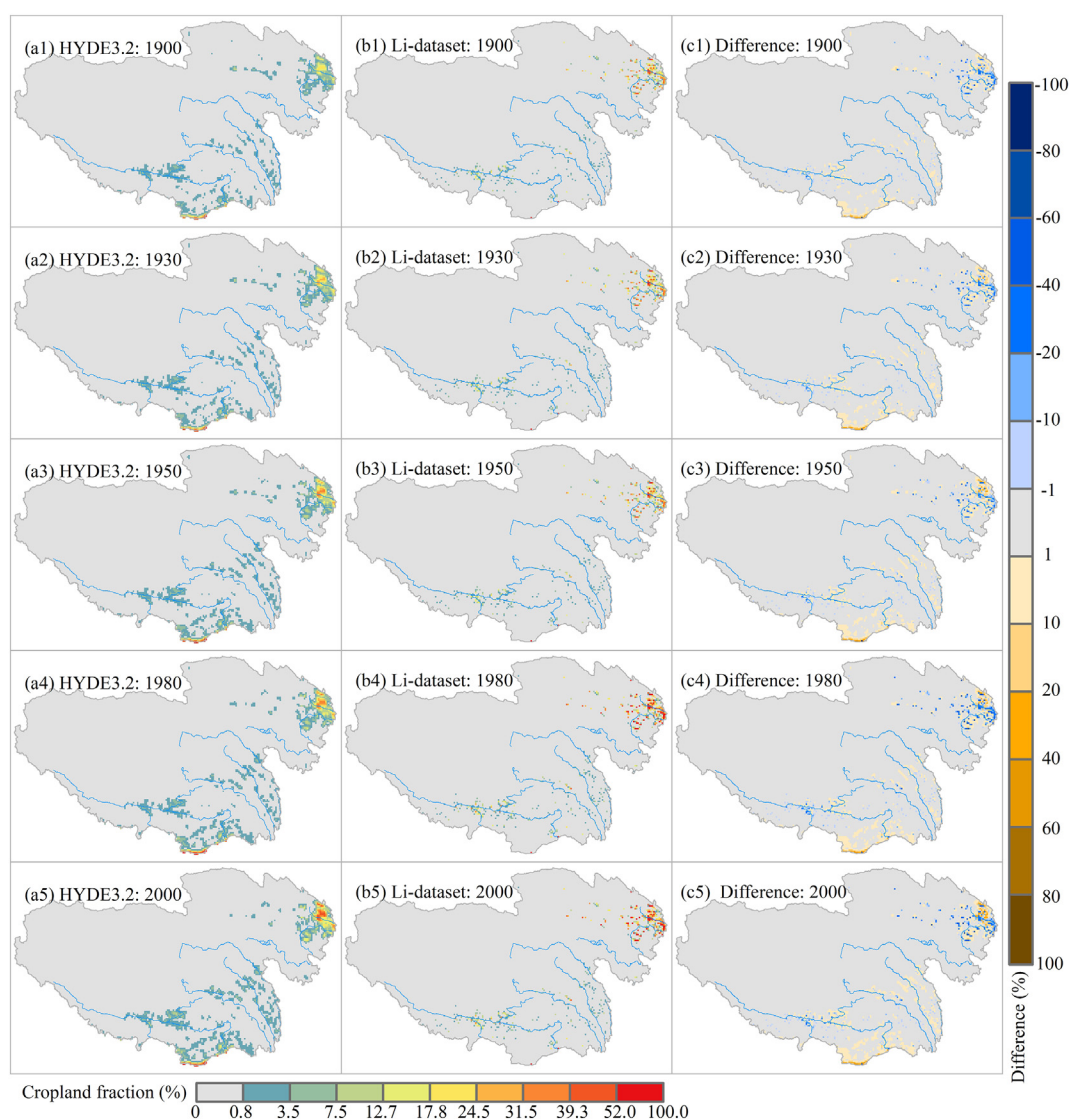


Fig. 6. Comparison of spatial patterns of cropland between HYDE3.2 and the Li-dataset for 1900–2000 on the Qinghai–Tibet Area.

fractional cropland area in HYDE3.2 tended to be broad and uniform while in the Li-dataset the distribution tended to be discrete, indicating that HYDE3.2 cannot grasp fine details of cropland distribution.

4.3.3. Comparison between SAGE and the Li-dataset

Generally, the spatial patterns of cropland on the QTA by SAGE and the Li-dataset for 1900–2000 were quite close and the cultivated regions were mainly the YHRV and the YRTT. However, there remained some differences between the databases (Fig. 7). For SAGE the area of cropland and the extent of the spatial distribution were clearly greater than those of the Li-dataset. In particular, SAGE has allocated too much cropland to southeastern Tibet, a region where access would have been difficult because of the complex terrain.

From the perspective of change trends, the Li-dataset showed that the spatial patterns of cropland on the QTA were nearly stable for 1900–1950. SAGE also revealed that the spatial pattern of cropland in the YRTT was stable. Unlike the Li dataset, however, the intensity of land reclamation in the YHRV showed a gradual increase. It can also be seen from the difference maps for 1900–1950 that SAGE overestimated significantly the distribution of cropland. Positive differences across the YRTT region and eastern Tibet occurred; however, for

1900–1950 the negative differences in the YHRV decreased and the positive differences increased.

Differences can also be detected between SAGE and the Li-dataset for 1950–2000 (Fig. 7). For this period, the Li-dataset showed that the cropland in the YHRV and the YRTT areas had expanded and the land reclamation intensity had increased. But the distribution of cropland in the YHRV and the land reclamation intensity were nearly stable in SAGE. In addition, in SAGE, the expansion of cropland was very noticeable in the southeast of Tibet, but the cropland distribution along the Lancang-Mekong and Nu-Salween Rivers shrunk. It can be seen from the difference maps that for 1950–2000, the positive differences between SAGE and the Li-dataset in the YHRV region decreased, and the negative differences increased. In the YRTT area, the positive differences between the two datasets remained dominant and spread from the YRTT area to the south-eastern direction.

In conclusion, over the past 100 years, SAGE overestimated significantly the cropland area and its distribution in Tibet. Also, expansion of the spatial distribution of cropland in southeastern Tibet was inconsistent with the actual situation. There were many grid cells with large differences in cropland distribution between SAGE and the Li-dataset in the YHRV region. The distribution of cropland in central Qinghai

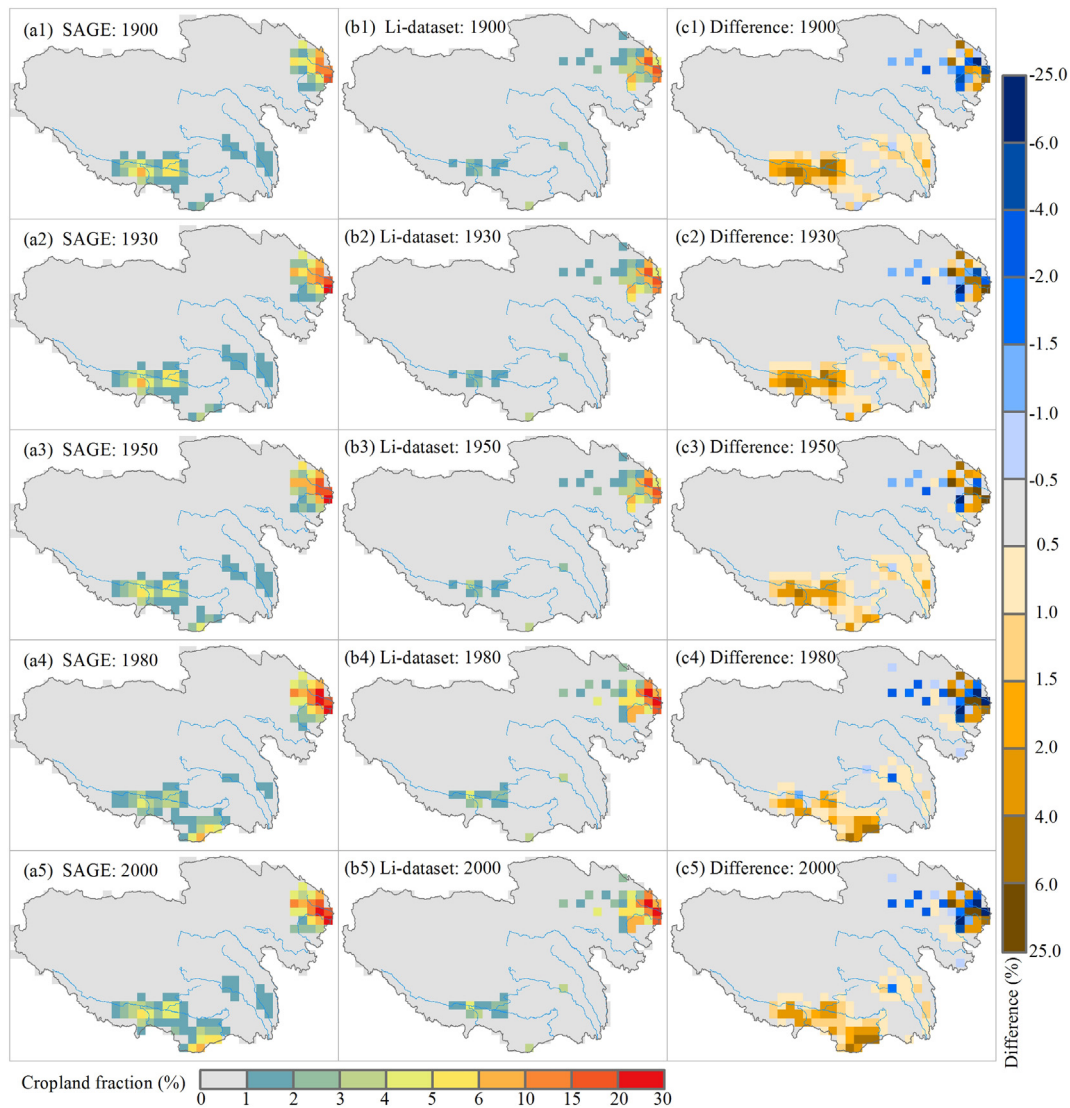


Fig. 7. Comparison of spatial patterns for cropland between SAGE and the Li-dataset for 1900–2000 on the Qinghai–Tibet Area.

Province was not accurately reflected in SAGE, resulting in negative differences between the two datasets.

4.4. Differences in spatial patterns of pasture

4.4.1. Comparison with grassland in CLUDs

A spatially explicit historical pasture dataset for the QTA is not available; thus, the global historical land use scenarios were compared with grassland in remotely sensed CLUDs for 2000 (Fig. 8). Because of the lacking differentiation between natural and anthropogenic grasslands in remotely sensed data, the grassland in CLUDs include grassland for grazing, and grassland not used or not suitable for grazing, which means the grassland scope as defined in CLUDs is greater than that for pasture that is land used for grazing in global scenarios. It can be seen that HYDE, particularly HYDE3.2, overestimated the area and geographic distribution of pasture on the QTA substantially. In comparison with grassland in CLUDs, the distribution range of pasture in HYDE3.1 and HYDE3.2 was too large in the mid-west of Qinghai Province and southeastern Tibet. These regions are dominated by unused land (including sandy land, Gobi, Salina, swamp land, bare soil, bare rock, desert, and tundra), sparse grassland (i.e., grassland with canopy coverage between 5% and 20%), and woodland (including shrub, and woods) based on vegetation atlas of China (Hou, 2001a) and remotely sensed data

(Fig. S1 in Supplementary material). Such features were also reflected in the low net primary production (NPP) of alpine grassland, low carrying capacity for grazing, and low population density for these regions (Gao et al., 2013; Zhang et al., 2014). Although some grazing activities exist in these regions for growing season (from April to October) on the QTA, the number and the density of domestic animals are small (Fig. 9(a3), (b3)). The fact that HYDE3.2 revealed that a large range of land was used for grazing in these regions is clearly unreasonable.

In addition, the distribution of land used for grazing in the mid-western parts of Tibet (e.g., the Chang Tang Plateau in Fig. 1) as given by HYDE3.1 and HYDE3.2 is also unreasonable (Fig. 8). Although a lot of grass is detected in this region in CLUDs, the herbaceous vegetation is mostly sparse grassland with low and medium coverage (i.e., canopy coverage between 5% and 50%. Fig. S1 in Supplementary material) which is very fragile ecologically and sensitive to human activities, and the NPP is very low (Gao et al., 2013; Zhang et al., 2014), conditions which clearly cannot satisfy demand by a large number of livestock for water and grass. A low carrying capacity per unit area of grassland for grazing is also identified and only some form of mobile pastoralism can be supported here (Zhao et al., 2015). In addition, many studies show that the human activity intensity for this region is low and limited (Fan et al., 2015; Li et al., 2018b; Liu, 1992; Sanderson et al., 2002; Venter et al., 2016; Zhong et al., 2008). Specifically, prior

to 1990, the total scale of human activities was relatively small and the Chang Tang Plateau is not disturbed much by human activities (Fan et al., 2015). The human footprint score, a quantitative evaluation of human influence on the land surface, is very low in the Chang Tang Plateau for the early 1990s (Sanderson et al., 2002) and 2009/2010 (Li et al., 2018b; Venter et al., 2016), and it is referred to one of Earth's remaining wilderness areas in the Anthropocene (Watson et al., 2016). This region was designated as the Chang Tang Nature Reserve with an area of over 334,000 km² in 1993, which means large scale grazing activities are seriously forbidden after 1993 (Li et al., 2018a) and also indicates that HYDE overestimated pasture area significantly in this region for 2000.

Compared with HYDE3.1 and HYDE3.2, the geographical distribution of pasture in SAGE is relatively reasonable, there being no a lot of pasture in the mid-western parts of the plateau since most grassland here illustrated in CLUDs (Fig. 8(b3)) is unsuitable for grazing. However, positive differences still exist in the eastern part of Qinghai Province, the YRIT, and eastern Tibet compared with grassland in CLUDs, indicating SAGE overestimated the pasture area in these regions. Note that further comparison is still needed for a comprehensive evaluation on the uncertainties of SAGE pasture distribution on the QTA.

4.4.2. Comparison with grazing intensity

As mentioned above, comparison between pasture in the global scenarios and grassland in CLUDs is only an initial evaluation given that the terms pasture and grassland are not defined in the same way. Therefore, a comparison between pasture in the global scenarios and grazing intensity was carried out further. The spatial patterns of pasture in HYDE3.1 and HYDE3.2 were close to each other (Fig. 8(a1)–(a2)), so only the latest HYDE3.2 and SAGE were compared with respect to grazing intensity. The spatial pattern of pasture in HYDE3.2 showed large differences compared with the spatial pattern of grazing intensity for 2000 and 2010 (Fig. 9). The pasture distribution in HYDE3.2 was

overestimated significantly, and too much pasture was allocated to the mid-western QTA. In addition, the increase of grazing intensity for 2000–2010 was not reflected in HYDE3.2. In terms of SAGE, the pasture distribution showed overall an agreement with the distribution of grazing intensity for 2000 and 2010, indicating the mid-eastern regions of the QTA were the main places for grazing activity. But differences still exist between SAGE and grazing intensity dataset, especially for the changes in spatial patterns for 2000–2010 (2007). An increase of grazing intensity for 2000–2010 occurred in mid-eastern Tibet and north-eastern Qinghai Province, while in SAGE an increase of pasture area for 2000–2007 is detected in the forested regions of southeast Tibet, which is clearly incorrect. Overestimation of pasture area in southwest Tibet is also detected in SAGE.

Overall, large uncertainties exist in HYDE3.2 scenario for pasture distribution on the QTA (Figs. 8, 9). The SAGE scenario captures the overall spatial pattern of pasture distribution but some uncertainties do exist for the changes in spatial patterns of pasture distribution.

5. Discussion

The evaluation of global historical land use scenarios is valuable for global or regional reconstructions with higher accuracy and for climate change modeling. Based on the regional cropland reconstruction Li-dataset, remotely sensed CLUDs, and grazing intensity dataset, the uncertainties of HYDE3.1, HYDE3.2, and SAGE scenarios in land use area and geographical distribution on the QTA were evaluated. Previous comparisons or evaluation studies have mainly focused on cropland (He et al., 2018; He et al., 2013; Li et al., 2010; Zhang et al., 2013). In this study, we not only evaluated cropland in the global scenarios, but also evaluated pasture, employing regional grassland/pasture inventory data, grassland (including grassland for grazing, and grassland not used or not suitable for grazing) in remotely sensed CLUDs, and grazing intensity dataset.

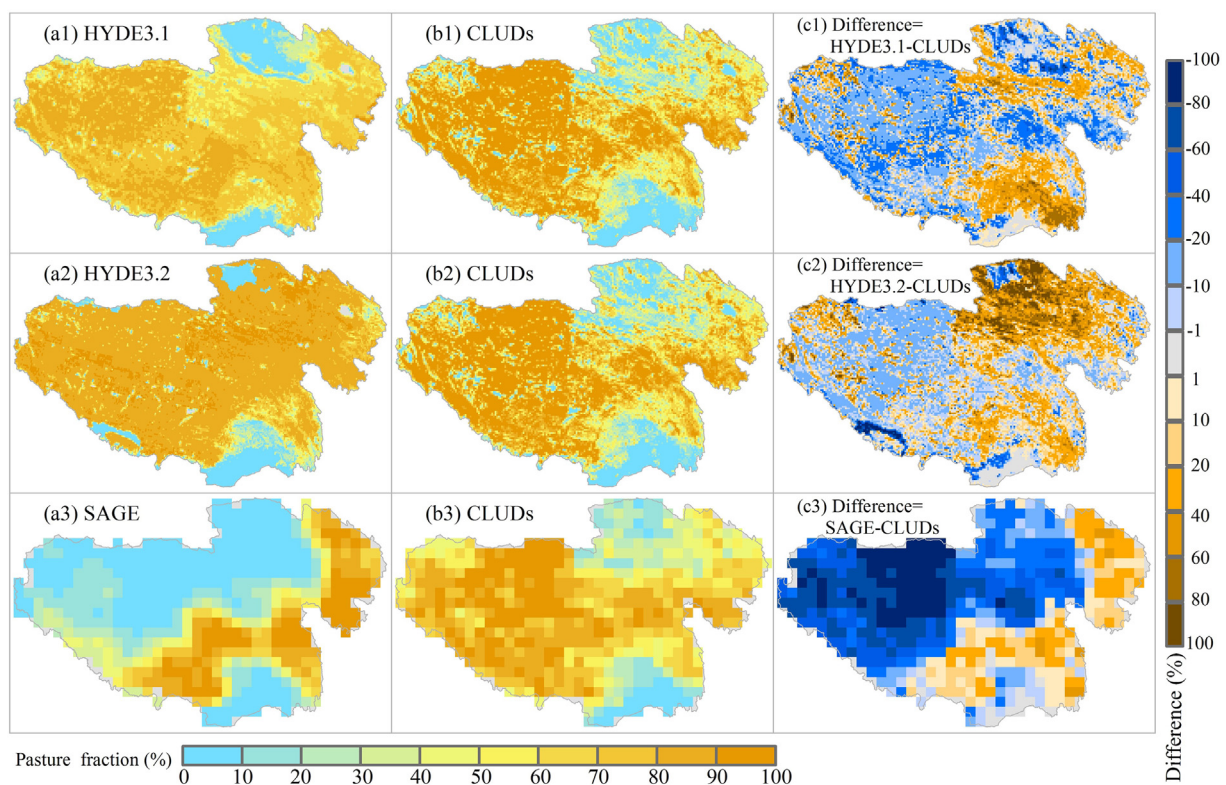


Fig. 8. Comparisons of pasture distribution in HYDE3.1, HYDE3.2, and SAGE with grassland distribution in CLUDs for the year 2000 on the Qinghai-Tibet Area. Because of the lacking differentiation between natural and anthropogenic grasslands in remotely sensed data, the grassland scope as defined in CLUDs is greater than that for pasture in global scenarios. The grassland in mid-western Tibet (e.g., the Chang Tang Plateau in Fig. 1) is mostly unsuitable for grazing, and it is referred to one of Earth's remaining wilderness areas (Watson et al., 2016).

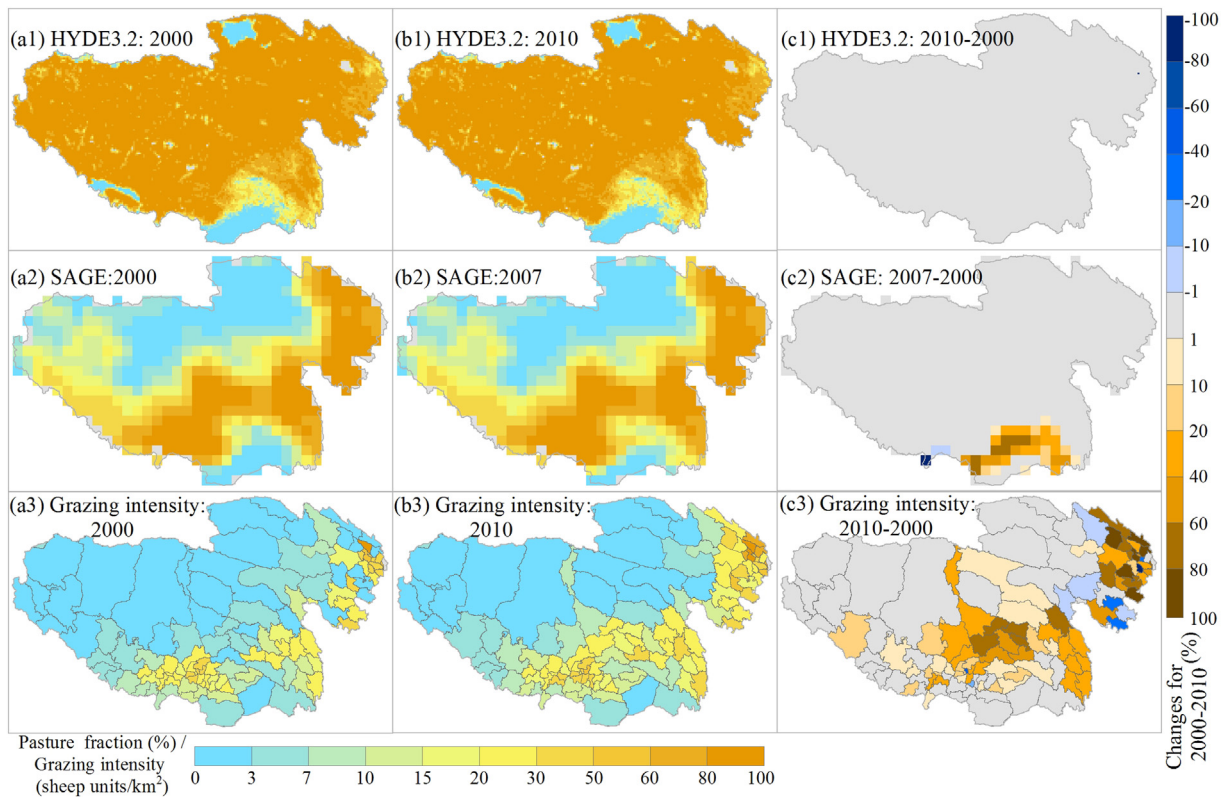


Fig. 9. Comparison of pasture distributions in HYDE3.2 and SAGE and spatial patterns of grazing intensity for 2000 and 2010 on the Qinghai–Tibet Area.

The comparison results show that HYDE3.2 agrees well with the regional reconstruction Li-dataset in cropland area, but HYDE3.1 underestimated and SAGE overestimated significantly the cropland areas of the QTA. HYDE3.2 and SAGE can only capture the overall spatial pattern of cropland distribution, and too much cropland was allocated to the forested region in the southeast of Tibet. HYDE (versions 3.1 and 3.2) overestimated substantially the pasture area and its distribution on the QTA, which is in agreement with the result of previous study that HYDE3.1 includes much higher percentages of pasture on herbaceous cover and sparse herbaceous or sparse shrub cover in Tibet (Phelps and Kaplan, 2017). The SAGE scenario captures the overall spatial pattern of pasture distribution with overestimation in southwest Tibet. The change tendency of grazing intensity for 2000–2010, however, was not reflected in the geographical distribution of pasture in HYDE and SAGE. Given these anomalies, possible reasons for such large discrepancies and suggestions on how to improve reconstructions of historical land use and climate change modeling are given.

5.1. Possible reasons for non-agreement of datasets

5.1.1. Land use inventory data

It can be seen from the reconstruction method of the global scenarios that all uncertainties in the estimates of historical land use inventory data will propagate to the spatial patterns of historical land use, which is illustrated by the fact that the overestimations of pasture inventory data in HYDE3.1 and HYDE3.2 for 2000 (Fig. 4) gave rise to a large range of land unsuitable for grazing on the QTA was used for grazing in the two scenarios (Fig. 8(a1)–(a2)). Therefore, it is important to identify the uncertainties in the historical estimates of land use area.

First, subnational or regional inventory data in these global scenarios lack sufficient detail, and estimates at a national level are too coarse for large countries, especially in the case of pasture. Compared with the estimates for cropland area on the QTA in HYDE3.1, the estimates in HYDE3.2 gave better agreement with the Li-dataset because more

regional statistics were included in the updated version of HYDE3.2 (Klein Goldewijk et al., 2017). Previous comparisons also concluded that HYDE3.1 gave better agreement with regional reconstructions of the traditionally agricultural regions in China than the older HYDE3.0 version because of the inclusion of updated historical estimates from regional studies (He et al., 2013). In terms of pasture area, the values for the QTA in HYDE3.1 and HYDE3.2 differed from each other for 1960–2000 (Fig. 4), with the values for HYDE3.2 being greater than that for HYDE3.1. However, the pasture areas in HYDE3.1 and HYDE3.2 for this period were both taken from FAO statistics without updates (Klein Goldewijk et al., 2017; Klein Goldewijk et al., 2011). Therefore, we can conclude that the differences in pasture area estimates between versions 3.1 and 3.2 for the QTA originate from the allocation of national level area values into 5 min grids based on different allocation algorithms in the two versions. If the provincial or county pasture areas for Qinghai Province and Tibet are available, the area differences for 1960–2000 shown in Fig. 4 caused by the allocation algorithm will be eliminated. Because of the inclusion of more sub-national level agricultural inventory data in SAGE (Ramankutty et al., 2008), the pasture distribution on the QTA in SAGE is much more spatially accurate than HYDE3.2 (Fig. 9). This argument is also supported by the fact that HYDE3.1 includes higher pasture fractions on bare areas in Australia but SAGE don't because the pasture area HYDE 3.1 allocated are mostly national-level while the area SAGE distributed are sub-national level (Phelps and Kaplan, 2017).

Besides, using population as a proxy for pasture area in the global scenarios is an explanation of great non-agreement between the global scenarios and grassland/pasture inventory data and local studies (Ge et al., 2008; Ge et al., 2000; Li et al., 2013; Liu et al., 2008; Wu, 2017) for 1950–1990. Local studies suggested a decrease of grassland/pasture area for Qinghai Province over the 20th century, while HYDE3.1 and HYDE3.2 showed that the pasture area on the QTA increased rapidly for 1950–1990. For the pre-1960 period, the pasture area for HYDE is estimated based on population data and the per capita pasture area. For

the post-1960 period, HYDE uses FAO statistics directly. One possible reason for the rapid increase may be the direct connection of the pasture area for the pre-1960 and post-1960 periods without calibration since FAO noted that their statistics are problematic especially for countries and regions with many grass types (<http://faostat.fao.org/site/375/default.aspx>, Ramankutty et al., 2008).

China is mostly subtropical with temperate monsoon climates. Concurrent periods of rain and heat are very suitable for planting and conducive to developing a “farming civilization”, which is also the environment basis for China as a “traditional agricultural country.” Therefore, although grassland areas are vast in China, the country has long been characterized by the development of large-scale cropland agriculture and small-scale pasture agriculture (He et al., 2018). According to inventory data from China's six major pastoral areas, i.e., Tibet, Inner Mongolia, Xinjiang, Qinghai, Sichuan, and Gansu, their grassland areas account for about 75% of total grassland area in China, but their animal husbandry output value only accounts for 15% of the national animal husbandry output (Fang et al., 2016). National anthropogenic grassland areas only account for 3% of natural grassland area (Ministry of Agriculture of the People's Republic of China, 2013). For thousands of years, the land use practices in China have suggested that cropland has been expanding with population growth, which has led to a decline in grassland area and shrinking spatial distribution (Ye and Fang, 2011). Clearly, land use practices in the United States and Europe are not the same as in China. Using population as a proxy and assuming that the per capita pastoral areas are constant or have changed minimally over the past hundreds or thousands of years do not apply to China.

Note that the difference in definitions between FAO pasture and China grassland/pasture inventory data and CLUDs is another reason for the non-agreement of datasets. The FAO pasture definition, which is used by HYDE and SAGE, is land used permanently (5 years or more) for herbaceous forage crops, either cultivated or growing wild (gazing land or wild prairie). But the grassland/pasture inventory data in China do not distinguish between grassland used for grazing and not used for grazing. Also, large inconsistencies still exist in the grassland/pasture area estimates of China even for the present day (Fang et al., 2018; Shen et al., 2016). And the remotely sensed CLUDs lack differentiation between natural and anthropogenic/grazed grasslands. For example, it is difficult to tell whether the grassland in the Chang Tang Plateau is used for grazing or not just based on the satellite images (Fig. 8(b1)–(b3)).

5.1.2. Spatial patterns

Clear differences in the spatial patterns for cropland are apparent for HYDE3.1, HYDE3.2, SAGE, and the Li-dataset for 1900–2000. The three global scenarios allocated too much cropland to eastern and southeastern Tibet, especially SAGE in the case of the 1950–2000 period and HYDE3.2, which just showed overall agreement with the Li-dataset for the cropland area. Even for the present day, HYDE3.1, HYDE3.2, and SAGE are significantly different from the Li-dataset, which is also a satellite-based reconstruction. One possible reason for the differences is that the accuracies of the reference maps for the three global scenarios derived from the satellite imagery are low. The land cover map LC-CCI for the 2010 epoch from the European Space Agency was used in HYDE3.2. In terms of correspondence with reference land cover classes, LC-CCI2010 has a low correspondence of 55.5%, compared with MODIS of 63% and Globelands30 of 57.2% (Tsendbazar et al., 2015). Also, a previous evaluation indicated that LC-CCI2010 was inadequate to monitor cropland areas due to the large cropland overestimations (Perez-Hoyos et al., 2017). In addition, the techniques employed by HYDE3.1, HYDE3.2, and SAGE integrating current remote sensing data and historical inventory data to obtain spatially explicit historical land use datasets are also responsible for the differences (Verburg et al., 2011). The altitude and slope for southern Tibet is low or small, and there are many rivers in eastern QTA. HYDE3.1 and HYDE3.2 overestimate the weights of slope and distance from the great rivers. As a result, too

much cropland is allocated here (Figs. 5, 6). SAGE overestimates the inventory cropland area significantly (Fig. 3). The overestimated areas are allocated to southern Tibet and eastern QTA which are only theoretically suitable for reclamation (Fig. 7). In fact, even for present, the population density for these places is low because of poor accessibility and only sporadic cultivated land can be observed (Fig. S1 in Supplementary materials).

In terms of the spatial pattern of pasture, greater differences than these in cropland exist between the global scenarios and CLUDs and grazing intensity (Figs. 8, 9). It is thought that the main reason for these differences is that the method used to obtain the current pasture map largely determined the spatial pattern of pasture for the historical period. In the land cover classification scheme of satellite-derived datasets, grassland not pasture is identified as a land cover class. Clearly, it is difficult to distinguish between natural and anthropogenic/grazed grasslands in satellite images. So, the methodology using pasture inventory data, which has great uncertainty, to calibrate the satellite-based grassland map to obtain the current pasture map may not be valid, especially for the QTA.

HYDE allocates national-level pasture area by combining potential natural vegetation from the BIOME1 biogeography model with weighting maps, producing a map of potential vegetation estimates more than actual land use distribution (Phelps and Kaplan, 2017). As a result, HYDE includes higher pasture fractions on the mid-western QTA where is mostly covered by bare land and sparse grassland and also cannot reflect the spatial patterns of grazing intensity.

5.2. Suggestions for re-construction and climate change modeling

In this section, some useful information is offered to global land use dataset producers to further improve their maps and suggestions are also given to aid climate change modelers. First, it can be concluded from this study and previous comparisons (He et al., 2013) that subnational- or regional-scale statistics will reduce the uncertainty of global scenarios substantially. So, collecting more regional-scale statistics, including records and estimates of historical land use and population, and using them to update the global scenarios should be a basic endeavor of land use dataset producers to improve their maps. In addition, besides population, other proxies (e.g., the number of livestock, grazing intensity) may also be used to estimate land use area or as evidences for cross-validation. For example, the grain yield and the name of historical settlements can be used to estimate cropland area (Feng et al., 2005; Zeng et al., 2011), and livestock population can be used to estimate pasture area (Ramankutty et al., 2008). Be careful during the update or estimate process because regional-scale statistics can also be plagued by over or under reporting, and/or varied definitions of land use (Phelps and Kaplan, 2017; Verburg et al., 2011). The FAO definition of permanent pasture which is employed in the global scenarios should be revised to better denote various pastures/grasslands on the QTA, and in China. As the accuracy of satellite maps used by the global scenarios is low for the QTA, a current satellite-based land use map with high accuracy is needed, particularly for grassland and/or pasture. In addition, solutions for remotely sensed products that already exist are also necessary, including downscaling remote sensing data (Atkinson, 2013) and filling in spatial gaps (Mariethoz et al., 2012).

Given that regional differences are large within the QTA and China, stratification reconstruction based on differences in agro-climatic conditions and resource endowments will show a better representation of region-specific conditions affecting cropland and pasture distributions. For China, the northwest is a pastoral region, and the southeast is an agricultural region. The characteristics of area and the distribution of pasture in pastoral and agricultural regions are significantly different from each other (Verburg and van Keulen, 1999). Compared with the traditional grazing activities on the QTA, much non-traditional grazing occurs in traditional agricultural regions with goats grazing along roads, dry river beds, and in fields after harvest, and pigs in back yards

(Ramankutty et al., 2008). It is difficult to estimate the area and distribution of pasture in pasture and agricultural regions using the same method and only a single land use category of “pasture” with no characterization of land use. It would be useful to define/different the land use more clearly (Phelps and Kaplan, 2017). Stratification reconstruction should also make full use of the land use records of temples which are distributed throughout the QTA.

Climate change modelers should note that HYDE3.2 estimated well the cropland area of the QTA for 1900–2000 while HYDE3.1 underestimated and SAGE overestimated the cropland area significantly. For cropland distribution, large differences exist between HYDE3.1 and the Li-dataset, and HYDE3.2 and SAGE captured just the overall spatial patterns of cropland distribution without fine details, and too much cropland was allocated to southeastern Tibet, especially for 1950–2000. In terms of area and spatial distribution of pasture, large uncertainties exist for HYDE3.1 and HYDE3.2 scenarios and they should not be used to model climate change because the pasture estimations do not accurately reflect grazing activity on the QTA. SAGE captured the overall spatial pattern of grazing activities on the QTA but some uncertainties still existed for the changes in spatial patterns of pasture distribution.

In this study, we evaluated cropland for 1900–2000 and pasture for 1950–2015 in the global scenarios on the QTA, an area of about 200 million km². Large uncertainties in the global scenarios were identified. And for deep past period, less information on land use is available and we infer that more uncertainty will exist (Klein Goldewijk et al., 2017), suggesting that the global scenarios can only be applied to broad geographical regions. Comprehensive and critical evaluation and even revisions are needed before the global scenarios can be used to model climate change at the regional scale.

6. Concluding remarks

The global historical land use scenarios made great contributions to the quantification of past LUCC at the subcontinental to global scales. They are widely used by modelers to quantify the effects of anthropogenic land cover change on climate from the regional to global scales. It is necessary to perform regional scale assessments of these global scenarios, identifying their uncertainties at the regional scale and pointing out directions for improvement. Based on the regional reconstruction Li-dataset, remotely-sensed dataset, and grazing intensity dataset, we perform a systematic evaluation of the three widely-used scenarios for the QTA. The comparison shows that the cropland area of the QTA in HYDE3.2 for 1900–2000 was close to that of the Li-dataset, whereas HYDE3.1 underestimated and SAGE overestimated significantly cropland area. Large differences exist between HYDE3.1 and the Li-dataset for the spatial patterns of cropland on the QTA. HYDE3.2 and SAGE captured only the overall spatial pattern of cropland distribution, and too much cropland was allocated to southeastern Tibet. HYDE3.1 and HYDE3.2 very significantly overestimated the pasture area and its distribution on the QTA. The geographical distribution of pasture in SAGE showed overall an agreement with the spatial patterns of grazing intensity at the county level, but the change tendency for grazing intensity for 2000–2010 was not reflected in SAGE.

Subnational or regional level land use inventory data with concise definitions will reduce the uncertainty of global scenarios substantially, especially for pasture. Note that specific definition and rigorous calibration are needed for the regional level data before they are included in the global scenarios. The FAO definition and estimates of permanent pastures and the use of population as a proxy for pasture area were found to be not suitable for the QTA and regions of China where there are large differences in natural conditions and culture. Using only a single land use category of “pasture” with no characterization of land use is insufficient, and it would be useful to define/different the land use more clearly. The accuracy of the reference maps of the two global scenarios derived from satellite imagery was low. Also, the methodology using

pasture inventory data to calibrate the satellite-based grassland map to derive current pasture maps was not appropriate, especially for the QTA where the grassland types are diverse, and the spatial patterns of grassland and pasture are very different.

Stratification reconstruction and developing maps that reveal current livestock density and overlaying these with the current herbaceous vegetation maps to obtain up-to-date pasture maps are suggestions for improving mapping capability. The global historical land use scenarios can only be used for broad geographical regions, and comprehensive evaluation is needed before they can be applied at a regional scale to model climate change.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2018.12.136>.

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